# Management of bivalve fisheries in marine protected areas

**Nielsen, Pernille; Nielsen, Mette Møller; McLaverty, Ciaran; Kristensen, Kasper; Geitner, Kerstin; Olsen, Jeppe; Saurel, Camille; Petersen, Jens Kjerulf**

*Published in:*
Marine Policy

*Link to article, DOI:*
10.1016/j.marpol.2020.104357

*Publication date:*
2021

*Document Version*
Peer reviewed version

**Abstract**

Marine protected areas are often designated in areas which represent important or historic fishing grounds. Within the European Union, the Natura 2000 (N2000) network of nature protection areas consists of Special Areas of Conservation and Special Protection Areas designated under the Habitats Directive and Birds Directive, respectively. In Denmark, an ecosystem-based approach to the management of bivalve fisheries has been implemented in a number of these N2000 areas, ensuring the sustainability of these fisheries and the conservation status of the designated areas. Here, we outline the key management strategies which have been implemented in the N2000 areas under the Danish Mussel Policy. These include the mandatory enforcement of monitoring systems on fishing vessels, acceptance of a maximum 15% cumulative fishery impact to specific ecosystem components, and a remarkable research effort to provide high resolution spatial habitat mapping. Additional strategies such as depth-based spatial restrictions, regulation enforcements, detailed assessments of fisheries impact, and documentation of positive effects of the ecosystem-based approach are also outlined. The results and lessons learnt outlined here are expected to be relevant to those concerned with the management and sustainability of fisheries activities in marine protected areas.

**Title**: Management of bivalve fisheries in marine protected areas

**Authors**:

Pernille Nielsen[1#]

Mette Møller Nielsen[1]

Ciaran McLaverty[1]

Kasper Kristensen[2]

Kerstin Geitner[3]

Jeppe Olsen[3]

Camille Saurel[1]

Jens Kjerulf Petersen[1]

[1] National Institute of Aquatic Resources, Technical University of Denmark, Danish Shellfish Centre, Øroddevej 80, DK-7900 Nykøbing Mors, Denmark

[2] National Institute of Aquatic Resources, Technical University of Denmark, Section for Marine Living Resources, Kemitorvet, DK-2800 Kgs. Lyngby, Denmark

[3] National Institute of Aquatic Resources, Technical University of Denmark, Section for Monitoring and Data, Kemitorvet, DK-2800 Kgs. Lyngby, Denmark

[#] corresponding author: peniel@aqua.dtu.dk

**Funding sources**: The Danish Ministry of Environment and food and the European Fisheries Fund have funded several research projects. This publication reflects the views only of the authors, and neither the European Union nor Danish Ministry of of Environment and food cannot be held responsible for any use which may be made of the information contained therein.

**Title**: Management of bivalve fisheries in marine protected areas

***Abstract:***

Marine protected areas are often designated in areas which represent important or historic fishing grounds. Within the European Union, the Natura 2000 (N2000) network of nature protection areas consists of Special Areas of Conservation and Special Protection Areas designated under the Habitats Directive and Birds Directive, respectively. In Denmark, an ecosystem-based approach to the management of bivalve fisheries has been implemented in a number of these N2000 areas, ensuring the sustainability of these fisheries and the conservation status of the designated areas. Here, we outline the key management strategies which have been implemented in the N2000 areas under the Danish Mussel Policy. These include the mandatory enforcement of monitoring systems on fishing vessels, acceptance of a maximum 15% cumulative fishery impact to specific ecosystem components, and a remarkable research effort to provide high resolution spatial habitat mapping. Additional strategies such as depth-based spatial restrictions, regulation enforcements, detailed assessments of fisheries impact, and documentation of positive effects of the ecosystem-based approach are also outlined. The results and lessons learnt outlined here are expected to be relevant to those concerned with the management and sustainability of fisheries activities in marine protected areas.

## *1 Introduction*

In recent years, the global extent of marine protected areas (MPAs) has increased substantially [1], such that MPAs are now considered a vital protection measure in marine conservation [2,3]. However, MPAs are often placed in areas of high biological production or value, meaning that their implementation can generate conflict between economic and environmental interests. Where MPAs restrict or displace fishing activities [4,5], stakeholders can understandably perceive such changes as a barrier to economic opportunities. This can lead to a negative view of MPAs, despite their potential as management tools that can ensure the environmental and economic sustainability of the fishery [1]. Since many MPAs operate at a local level, it could be easier to explore the possibilities for sustainable economic benefits from MPAs by e.g. regulated exploitation of shellfisheries [1].

Bivalve production takes place within the jurisdiction of MPAs in a number of countries in Europe. On-bottom culture of blue mussels, where mussel seed is translocated from natural beds to designated culture areas, is widely practiced in the Netherlands, Germany, Ireland and United Kingdom [6]. On the other hand, the exploitation of wild adult bivalves by dredge fisheries is less commonly undertaken within MPAs. There are, however, exceptions to this, such as cockle and clam fisheries in Poole Harbour UK [7], scallop fisheries in Scotland [8], flat oyster fisheries in Ireland [9], and fisheries for bivalves in Denmark. As these wild capture bivalve fisheries are less common, there has been little (or an absence of) reporting of successful fishery management strategies that have been implemented in MPAs and have improved the economic and environmental sustainability of fisheries. In Denmark, the production of blue mussels (*Mytilus edulis*), cockles (*Cerastoderma edule*) and European flat oyster (*Ostrea edulis*) is mainly accounted for by dredge fisheries of wild populations. The management of mussel and oyster fisheries in

Danish coastal waters has to date required a balance between the protection of vulnerable species and habitats, and the sustainable utilisation of marine resources. Furthermore, these fisheries represent economically and culturally important coastal fisheries in rural areas of Denmark [10,11]. Previously, this balance was achieved by implementing depth limits on fishing activities to protect important ecosystem components such as eelgrass. With the implementation of European Union (EU) directives such as the Water Framework Directive (WFD) (2000/60/EC), Marine Strategy Framework Directive (MSFD) (2008/56/EC), Species and Habitats Directive (92/43/EEC), and Birds Directive (79/409/EEC), fisheries management has been required to take greater consideration of potential environmental impacts of fishing activities.

A large part of Danish bivalve fisheries take place in areas (Figure 1) protected by the Habitats and Birds Directives. The Habitats Directive aims to ensure the conservation of characteristic habitat types and a wide range of rare, threatened or endemic animal and plant species, whereas the Birds Directive was set out to establish a framework and objectives for the conservation of all birds throughout the EU. However, protection provided by the Habitats and Birds Directives does not exclude the continuation of anthropogenic activities, provided these do not compromise the integrity of the designated species and habitats.

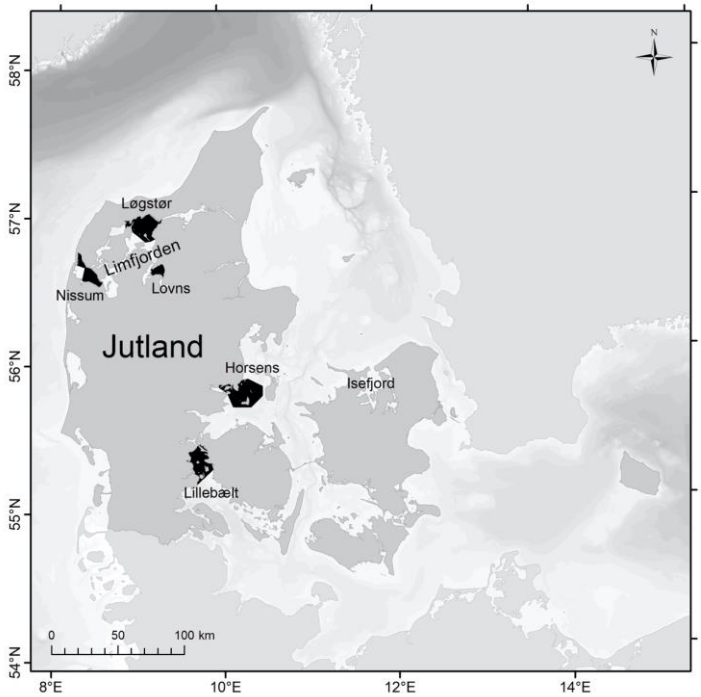


Figure 1. Map of Denmark. The locations of the five Natura 2000 sites where bivalve fisheries currently are allowed are illustrated in black.

During the early stages of implementation of the Habitats Directive and the WFD, Danish nature conservation NGOs were concerned whether sufficient effort was made to protect the coastal environment, and thus sought the exclusion of mussel and oyster fisheries within N2000 sites. As part of this process, nature conservation NGOs lodged formal complaints [12] with the EU Commission on several occasions from 2008 to 2012, with the purpose of opening a court case against the Danish government at the Court of Justice of the European Union (CJEU). These complaints related to permission provided by the Danish government to allow bivalve fisheries in selected N2000 sites, deemed to be of key importance to the industry. The CJEU opened procedures against the Danish government but the matter was closed in January 2014 and was never brought to trial. A key reason for this outcome was that the EU Commission accepted a

national consensus agreement, known as the Danish Mussel Policy [13]. The Policy represents an agreement between the Danish government, involved nature conservation NGOs, and the mussel industry, and defines the conditions necessary for mussel production with special focus on mussel fishery and nature conservation [13].

The aim of the present study is to demonstrate how the objectives of the Danish Mussel Policy have been met via a number of key management strategies. These include i) the monitoring of fishing activities using a high-resolution electronic monitoring system, ii) an intensive research effort to map the spatial distribution and vulnerability of essential ecosystem components, and iii) the management of specific bivalve stocks, key ecosystem components, and areas affected by fisheries. The experiences outlined in this study demonstrate how bivalve fisheries can be sustainably managed in MPAs. Furthermore, these approaches have ensured the preservation of N2000 habitats and species by the enforcement of stringent regulations and control measures. At each stage, these management decisions have underpinned by thorough science-based knowledge of environmental fishery impacts and habitat identification. These findings may also aid in identifying both viable alternative fishery management solutions to enhance the overall sustainability of fisheries, and to develop conservation priorities for essential habitats and species in MPAs in general.

## ***2 Danish bivalve fisheries***

### *2.1. Mussel and oyster fisheries*

Fisheries for blue mussels, cockles and European flat oyster in Denmark take place in coastal areas such as the Limfjorden, along the east coast of Jutland, and in the Isefjord (Figure 1). Between 2013 to 2018, total annual landings varied between 38,000 and 45,000 metric tons of blue

mussels, 4,000-8,000 metric tons of cockles, and 80-300 metric tons of flat oysters, where on average 35%, 0.1%, and 75% of the landings (data from The Danish Fisheries Agency) had been fished within five N2000 sites, respectively (Figure 1 and table 1).

The bivalve fishing fleet consists of vessels with a maximum engine size of 221 kW and maximum total length of 16 m, where each vessel is equipped with 2-4 dredges depending on the target species. Within N2000 sites, 2-4 mussel dredges (each dredge has a maximum frame width of 2 m and a maximum weight of 100 kg) are allowed per boat in the mussel and cockle fisheries, while only two smaller and lighter dredges are allowed in the flat oyster fishery (each dredge has a maximum frame width of 1 m and a total weight of 24 kg). The cockle fishery is currently not an independent fishery in the Limfjorden but as a by-catch of the mussel fishery. The mussel and oyster fisheries in N2000 sites are also regulated by e.g. closed areas, minimum depth limit for fishery, closure periods, maximum quotas for specific areas, minimum landing sizes, individual weekly and daily quotas, maximum number of vessels in each fishing area and logbook reporting. Furthermore, these general regulations are adjusted accordingly to the specific fishing areas and the targeted species of each N2000 site. In addition, the mussel and oyster fisheries in the Limfjorden (Figure 1 and table 1) are managed by the Foreningen MuslingeErhvervet (The mussel fishers and industry association) that coordinates quotas and pools, opening of fishing areas and runs the monitoring program for food safety according to the European Food Law EC (854/2004).

| Fishing areas | Marine area ($km^2$) | Species fished | Protected fish species | Protected bird species | Protected marine mammals |
|---|---|---|---|---|---|
| Løgstør Bredning (Limfjorden) | 316 | Blue mussels Cockles Flat oysters | 0 | 5 (1) | 2 |
| Lovns Bredning (Limfjorden) | 68.5 | Blue mussels | 2 | 2 (1) | 2 |
| Nissum Bredning (Limfjorden) | 172 | Flat oysters | 1 | 22 (2) | 2 |
| Little Belt (East coast) | 284 | Blue mussels | 0 | 15 (3) | 1 |
| Horsens (East coast) | 427 | Blue mussels | 0 | 11 (4) | 3 |

Table 1. The total marine area ($km^2$), targeted species, number of designated fish, bird and mammal species in five N2000 sites in Denmark, where environmental impact assessments of bivalve fisheries have been carried out. In brackets = number of mussel-eating bird species *[14-18]*.

### *2.2. The Danish Mussel and Oyster Policy and the Mussel Committee*

The Danish Mussel Policy was adopted in June 2013 and evaluated in 2017, subsequently leading to the revised Mussel and Oyster Policy (MOP) in May 2019. The ecosystem-based approach set out in the original Mussel Policy was maintained throughout the MOP, with the aim of ensuring that the management of fisheries in the N2000 sites can provide a balance between opportunities to develop the bivalve fishing industry, and the advancement of environmental conservation using scientific tools. Bivalve fisheries should therefore not act as an obstacle to achieving favourable conservation status for designated habitats and species in the N2000 sites [19]. Although the MOP was designed to primarily address the requirements of the Habitats Directive, it also takes into account WFD quality elements e.g. in the case of angiosperms (i.e. eelgrass, *Zostera marina*).

The MOP mitigates the effects of fisheries in N2000 areas via the estimation of acceptable cumulative areal impact to four key ecosystem components (ESCs), namely mussels, eelgrass,

macroalgae and benthic fauna, which are indicators of conservation status for relevant marine habitats. The upper limit for total cumulative areal impact for each of the ESCs mussels, macroalgae and benthic fauna is 15%, whereas for eelgrass it is 0%. The cumulative area is calculated based on the total marine area of the N2000 site that can be impacted by the bivalve fishery, whereas time period varies between the ESCs, due to differences in estimated regeneration times, but can also vary for the same ESC between N2000 sites as a result of differing environmental conditions and conservation status.

The Danish Mussel Committee was founded in 2003 and consists of representatives from the Danish government, nature conservation NGOs, researchers, mussel and oyster fishers, and the mussel industry. The Mussel Committee played a central role in defining the conditions for bivalve fishery, as outlined in the MOP, to promote environmentally and economically sustainable mussel production in Denmark. After the adoption of the original Mussel Policy in 2013, the Mussel Committee has been an active and dynamic forum, where e.g. research results, political decisions and fishery management actions are presented and discussed, ensuring the involvement of all the stakeholders in the mussel and oyster fishery management.

### *3. Monitoring tools and methodologies*

To support the ambitious goals of both maintaining mussel and oyster fisheries in N2000 sites and ensure the conservation status of designated habitats and species in the N2000 sites, extensive habitat mapping and science-based site-specific knowledge are required. As most inner Danish waters are heavily eutrophic [20,21], the national environmental monitoring programme (NOVANA) was originally established to detect and monitor the effects of excess nutrient run-off. However, the programme is currently used to monitor the health of coastal waters according to

several WFD and MSFD indicators. In order to distinguish between effects of different pressures, which either affect the environment at the scale of entire sites/basins (e.g. nutrient run-off), or at the scale of localised impact areas (e.g. fisheries), new types of data and development of tools are required. New research and documentation efforts to support the bivalve fishery management for each of the four ESCs in each of the five N2000 sites (Table 1) were developed in a stepwise manner and are currently being applied. The assessments of bivalve stocks were already implemented in the management of the bivalve fisheries but developed further by a new statistical model. The mapping of eelgrass and macroalgae habitats was a first priority, starting in 2011-2012 in two out of the five N2000 sites. This mapping is now fully implemented in the management of all five N2000 sites since 2017. Benthic fauna was first surveyed in 2017, the assessments finalised in 2019, and management recommendations subsequently implemented in the 2020/2021 fishing season.

*3.1. Area affected by the fishery – the black box system*

In order to accurately estimate the cumulative areal impact, “black box” (BB - BlackBox R2, Anchor Lab, Copenhagen) systems are fitted on board all fishing vessels operating in N2000 areas. Use of the system is compulsory and has been implemented on bivalve fishing vessels since the 2012/2013 fishing season. BB provides high resolution fishing data by recording the vessel's fishing activities in 10 seconds intervals. Combined with logbook data on target species, dredge type, dredge width and number of dredges, the impact of each fishing vessel can be assessed, and subsequently summarised per vessel. The total impacted area per N2000 site for each fishery (mussels and oysters) is estimated by adding the impacted areas for all vessels within a fishing season. The cumulative areal impact for the ESCs are calculated by estimating the impacted area

per fishing season and cumulated in accordance with the specific regeneration time for each ESC. Each year, the results of this are compiled in an environmental impact assessment (EIA).

*3.2. Environmental impact assessment*

The annual EIA for each N2000 site assesses potential impacts caused by specific quotas applied for by the fisheries organizations. The EIA only includes assessments of the ESCs, designated marine habitats and species (under the Habitats and Birds Directives), that may be impacted by the fishery, meaning that fishery exclusion areas in shallow areas are not included e.g. lagoons or salt marshes. Identified geogenic reefs are protected by a 100 m buffer zone, where bivalve fisheries are forbidden, while biogenic reefs protections have not yet been appointed by the authorities.

The designated species and number of protected species varies between the five different N2000 sites (Table 4) and can be categorised into three main groups; fish, marine mammals and birds. The assessment of fishery impacts to marine mammals includes disturbance, while birds are also assessed in terms of reduced blue mussel biomass for the mussel eating bird species. Fish species are assessed in terms of bycatch and disturbance of feeding and breeding habitats.

The time period over which the cumulative areal impacts are assessed for each ESC is based on the regeneration times set in the MOP and include several past fishing seasons in combination with coming season. The regeneration times range from 3 years for blue mussels, >20 years for eelgrass and 5 years for macroalgae for all five N2000 sites (Table 1) but vary between 3 to 5 years for benthic fauna according to the specific N2000 sites. The impacted area for past fishing seasons is calculated using BB data, and the estimated impacted area for the coming fishing season is calculated using i) estimates of mussel biomass density (kg $m^{-2}$) from annual stock assessment

surveys, ii) the quotas (t) applied for by the fisheries associations and iii) catch efficiency of 65% for the commercial light mussel dredge [22].

The preparation of EIAs follows a three-year cycle. A full EIA is conducted every third year and includes updated monitoring data of ESCs, assessment of fishery impacted areas for all four ESCs, and fisheries impact assessments for marine mammals, fish and birds. In the years between, supplemental EIAs are conducted to include stock assessments of ESC blue mussel, reduced surveys of eelgrass and macroalgae, assessment of fishery impacted areas for all four ESCs and fisheries impact on mussel eating birds. Each ESCs are mapped for each N2000 in order to quantify the amount of impacted area by the fishery.

### *3.3 Ecosystem components monitoring methodology*

#### 3.3.1 ESC blue mussels

In order to open a N2000 site for mussel or oyster fisheries, an annual stock survey and size distribution of mussels or oysters within the N2000 site must be carried out prior to the fishing season. Each N2000 site is split into grid cells of 0.5 x 0.5 $km^2$ to layout a stations grid of 23-95 fixed sampling stations in the different areas (Figure 1 and table 1). The distribution of station grids is undertaken to obtain a regular geographical distribution of samples in each of the surveyed area. One haul is carried out at each station using a down-scaled (1 m width) commercial light mussel dredge [22]. The length of each dredge track is determined by noting the start and end GPS-positions of the boat during fishing (i.e. relative dredge position depending on wire length). On board, total wet weight is determined, and the catch is sorted into targeted species (mussels or flat oysters), empty shells, stones and other invertebrates. All fractions are weighed

separately (more information see [23,24]). At each station, shell height of all or a maximum of 200 individuals of the target species is measured.

Further to the above, a new statistic model was developed to predict the spatial distribution of mussels within the surveyed area and to estimate the total annual mussel stock. However, the type of data collected in the annual surveys can be problematic to analyse using standard statistical models. This is due to typically skewed frequency distributions with many zero catches and some very large catches, which cannot be described appropriately by the classical distribution types. To deal with this, a delta log-normal distribution is used as basis for the statistical models [25]. By using this approach, a certain probability of a zero capture in each grid cell is assumed, whereas grid cells with a catch different from zero is assumed to follow a logarithmic normal distribution. The new statistical model predicts the expected catch (kg ±SD) in each grid cell at a given time and place, which combined with an estimated density dependent dredge efficiency for the survey dredge is used to estimate the stocking density (kg $m^{-2}$) in the grid cell as: $D = 0.073*C^{1.696} + C$, where D is the mussel stock density (kg $m^{-2}$) and C is the catch of mussels (kg $m^{-2}$). The total stock estimate (±SD) for the entire N2000 areas is obtained by summing all grid cell (More details in supplements).

### 3.3.2 ESC eelgrass

To ensure zero impact on eelgrass beds from fisheries, eelgrass boxes are designated as a part of the annual EIA in relevant N2000 sites. The boxes exclude all fishing activities and are delimited on the basis of video surveys in combination with GIS modelling. The boxes are not based on depth limit but rather on potential distribution of the eelgrass, thus allowing the fishing to occur where no eelgrass is found or where conditions are not suitable for (re-)establishment. From video

surveys, eelgrass is mapped annually in May-June. A full survey is conducted every third year, while only a reduced survey (approx. 10%) is conducted in the years between. Dependent on the specific N2000 site (Table 1), a full survey consists of 144-349 video transects each covering 90-100 m seabed. These are undertaken at a specific depth following the bathymetry and parallel to the coast. From the video footage, eelgrass presence is categorized: 0) no eelgrass, 1) seedlings, 2) patches and 3) beds. Point observations are then interpolated to the entire area using spline with barriers in ArcGIS, where depth is the barrier, and used to describe the actual distribution. This layer is furthermore reclassified into five categories (Table 2) and used as one of nine input layers that are used in a GIS based site selection model highlighting areas with potential for eelgrass establishment.

| | Reclassified value for GIS model (1-5) | |
|---|---|---|
| Original value (0-3) | Eelgrass | Macroalgae (OM and NOM) |
| -1-0.5 | 1 | 5 |
| 0.5-0.8 | 2 | 4 |
| 0.8-1.1 | 3 | 3 |
| 1.1-2.1 | 4 | 2 |
| 2.1-4 | 5 | 1 |

Table 2. Original value after interpolation from point observation (0-3) of eelgrass, opportunistic macroalgae (OM) and non-opportunistic macroalgae (NOM) and reclassified value used in the GIS based site selection model.

The model has been calibrated and validated for various fjords in Denmark (for specific details see [26,27]) and is currently developed for all five Danish N2000 sites, where shellfish fishery is allowed (Table 1). It comprises a weighted overlay model consisting of parameters that affect eelgrass establishment: physical exposure, organic content in the sediment, frequency of resuspension events, benthic light availability, oxygen conditions, and the presence of lugworms,

eelgrass beds, opportunistic macroalgae and ballistic species of non-opportunistic macroalgae. Ballistic species are species that due to e.g. air bladders or tissue drag, can drift around still attached to a substrate and cause scouring over the sediment surface that leads to potential damaging of eelgrass seedlings [28].

The model output is a map predicting areas with optimal, good and bad conditions for eelgrass establishment. The final eelgrass boxes are designated as areas with good and optimal conditions, in addition to a general 300 m buffer zone to avoid indirect impact of fishery from settlement of resuspended sediment on the eelgrass. In addition to the eelgrass boxes, general depth limits specific to each N2000 site are imposed prohibiting fisheries at depth below 2-5 m mainly due to other conservations preservations (e.g. see section 4.2).

### 3.3.3 ESC macroalgae

The ESC macroalgae is surveyed by video transects similar to eelgrass (section 3.2) with two main purposes: i) to map the macroalgae distribution and determine the reduction factor used to calculate the cumulative area impacted by fishery (section 4.2) and ii) to provide macroalgae input for the eelgrass model (section 3.3.2). From the video footage, presence of total macroalgae, opportunistic macroalgae and ballistic species of non-opportunistic macroalgae is categorized into four categories: 0) none, 1) low, 2) medium and 3) high, and point observations are then interpolated to the entire area using spline with barriers in ArcGIS (depth as barrier).

As all macroalgae species are protected equally with the MOP, the resulting map of total macroalgae is used directly in the EIAs as well as to determine the reduction factor for the ESC macroalgae (Section 4.2). The parameters OM and NOM are used as input for the eelgrass model, since unattached drifting OM and ballistic NOM are known to potentially affect the eelgrass

establishment negatively [26,27]. The interpolated layers of OM and NOM are reclassified into five categories (Table 2) before being used in the eelgrass model (details in [26,27]).

### 3.3.4 ESC benthic fauna

Since the implementation of the MOP in 2013, and until the end of the 2019/2020 fishing season, the regeneration times of benthic fauna were set at between 2-4 years (N2000 site depending). These regeneration times were originally based on expert judgement, based on benthic community data gathered by the national environmental monitoring program (NOVANA). The NOVANA surveys are undertaken biannually and involve the collection of benthic samples from fixed locations in each of the N2000 sites. During the period 2017-2019, the monitoring data were supplemented by a benthic sampling programme (N2017) undertaken to assess bottom fishery effects in each of the N2000 sites [29]. The combined data sources were also used to map the distribution of benthic communities in each N2000 site, and to provide updated benthic community regenerations times. The combined NOVANA/N2017 dataset comprises roughly 360 samples across the five N2000 sites and provides a considerably improved spatial coverage and resolution of data available to inform the management of benthic fauna. To describe the distribution of benthic communities across the fishing grounds, multivariate cluster analysis (based on Bray–Curtis similarity) are used to group stations with similar faunal composition within each of the N2000 sites. As benthic communities are often comprised of many species, of which few typically dominate, the key discriminating species between communities are identified using Similarity Percentage analysis (SIMPER) [30]. Both clustering and determination of key species are based on benthic biomass, and the SIMPER identifies the species which account for the majority (≥90%) of differences between groups.

To describe the sensitivity of these benthic communities to fishing, and to validate the regeneration times, the typical lifespan (or longevity) of the benthic communities are estimated. Lifespan is described according to four longevity categories (<1yr, 1-3yr, 3-10yr, and >10yr) using an existing trait database [31]. Using these categories, the estimated regeneration times for each of the community clusters and each N2000 site are calculated using estimated recovery rates of benthic fauna from trawl fisheries provided by [32]. The regeneration times of each community cluster are estimated using the key discriminating species of the cluster determined by the SIMPER. However, the regeneration time of each N2000 site is based on all fauna recorded in the site (or, 100% of biomass).

## *4 Løgstør Case Study: complying with the MOP*

In the following sections we use the N2000 site Løgstør Bredning (Løgstør Broad) (Figure 1) as a case study to demonstrate how bivalve fisheries are regulated in accordance with the goals of the MOP. Furthermore, the Løgstør case study provides an example of how high-resolution electronic monitoring can be combined with detailed mapping of the distribution and vulnerability of essential habitats, to sustain conservation and fisheries objectives via an EIA. An outline of the approach and information included in the full EIA, undertaken every third year (see section 3.2) is presented below. The site-specific regeneration time of ESCs in Løgstør Bredning are >20 years (eelgrass), 3 years (mussel), 3 years (benthic fauna) and 5 years (macroalgae). Based on this, the area impacted by the mussel fishery is summed over these time periods for each ESC. Bivalve fisheries in the other N2000 sites are managed similarly, although the regeneration times for benthic fauna differ depending on the N2000 site in question (see section 3.2).

*4.1. Distribution of ESCs in Løgstør Bredning*

4.1.1 Blue mussel

To ensure sustainable bivalve production over time, an assessment of the stock(s) is required before fishery management measures can be implemented [33]. The estimated distribution and density of mussel biomass (kg $m^{-2}$) for 2017 is presented in Figure 2. The model estimated that the average biomass density (±SD) was 0.14 ± 0.03 kg $m^{-2}$ and total mussel stock biomass (±SD) within the broad was 44,514 ± 9,257 tons.

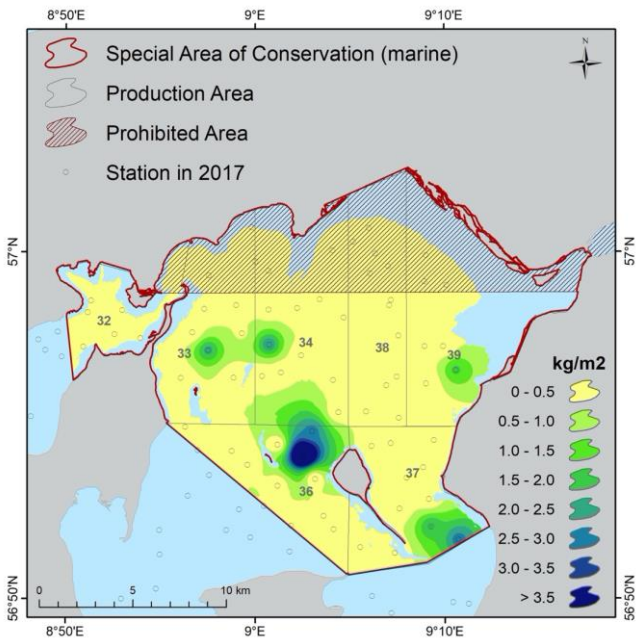


Figure 2. Estimated biomass density (kg $m^{-2}$) in the N2000 site, Løgstør Bredning, Limfjorden in 2017. Black circles indicate sampling stations.

4.1.2 Eelgrass

In Denmark, the depth limit of eelgrass is used as a bioindicator of ecological status. This is as water clarity (and phytoplankton concentrations) directly regulate the extension of seagrass into deeper water. This depth limit is defined as the maximum depth of 10% eelgrass cover [34].

Eelgrass distribution in Løgstør Bredning is assessed in the year prior to a fishing season. In 2016, the eelgrass was relatively scarce in Løgstør Bredning, and restricted to a few delimited areas at shallow water of 1-3 m (Figure 3 left). Patches of eelgrass can occur ephemerally in Limfjorden, and as a result, frequent surveys are needed to detect temporal variations. For example, eelgrass in Løgstør Bredning was found in two new areas in 2016 compared to 2013, while eelgrass had retreated to more shallow water in other areas. A comparison of the actual (Figure 3 left) and potential distribution of eelgrass obtained from modelling (Figure 3 right) reveals a high degree of congruence, suggesting a good ability to predict suitable seagrass areas with the developed GIS tool. The relevance of this is that the aim of the MOP is not only to protect the current eelgrass beds, but also areas where eelgrass potentially can re-establish to comply with the goals in the WFD. Hence, eelgrass boxes are designated based on actual distribution as well as potential future distribution.

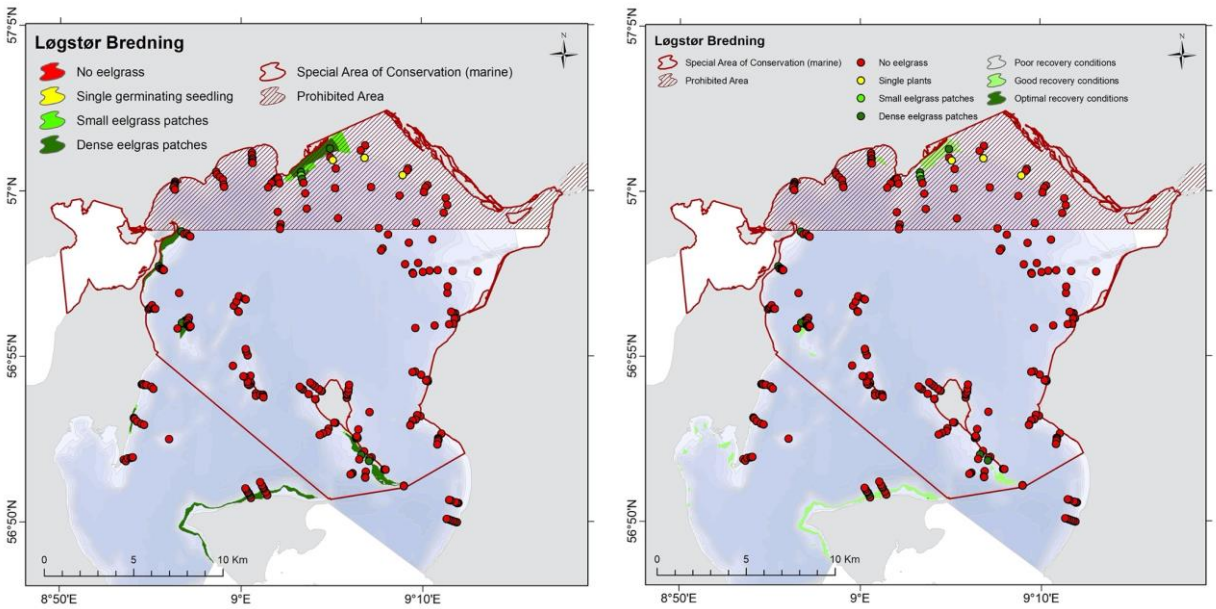


Figure 3. Left: Actual eelgrass distribution in Løgstør Bredning in 2016 based on results from the video survey. Circles represent point observations and light and dark green colours show distribution of eelgrass patches and eelgrass beds obtained by interpolation. Right: Potential distribution of eelgrass in Løgstør Bredning based on modelling. Circles

represent point observations from the video survey. Light and dark green colours represent areas with good and optimal condition for eelgrass establishment.

Monitoring and modelling in relation to the 2017/2018 fishing season resulted in the designation of six eelgrass boxes inside the N2000 area (A1-A6) and three outside the N2000 site (B1-3) (Figure 4). The three eelgrass boxes outside the N2000 site (B1-B3) are not included in the EIA.

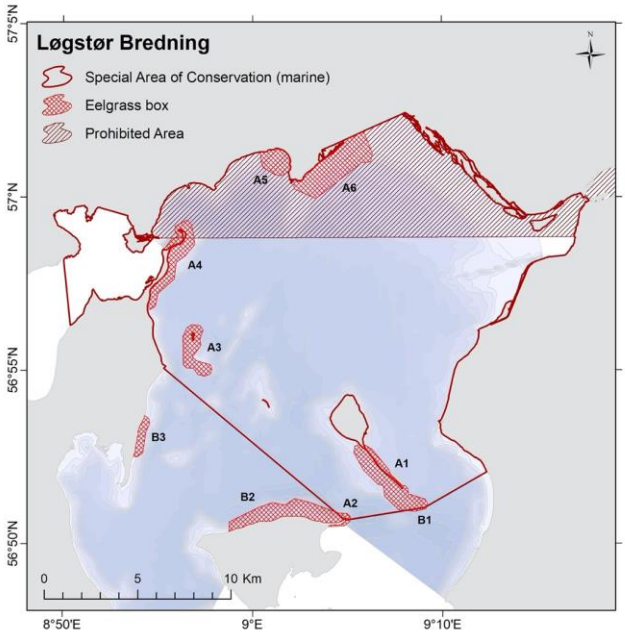


Figure 4. Eelgrass boxes in N2000 site, Løgstør Bredning for the fishing season 2017/2018. Boxes are designated on the basis of a full video survey in 2016 and modelling of potential areas for eelgrass re-establishment. Eelgrass boxes A1 to A6 are located inside the N2000 site, whereas eelgrass boxes B1 to B3 are located outside the N2000 site.

### 4.1.3 Macroalgae

Macroalgae constitutes one of the main biological quality elements proposed to classify the ecological status of a water body under the WFD. Consequently, the potential effects of fisheries on macroalgae require assessment to ensure ecological status is not adversely affected. The 2016

video survey in Løgstør Bredning recorded macroalgae at 83% of the transects (Figure 5). The highest densities and diversity of species were found at shallow waters (1-3 m), whereas densities at deeper waters were generally lower, less diverse, and primarily dominated by filamentous species. The dominant species at shallower areas was the invasive *Sargassum muticum*, forming dense beds (category 3) at 32, 23 and 19% of the stations at 1, 2 and 3 m depth respectively. This species was 10-40% more frequent than all other perennial macroalgae species combined. Furthermore, comparing data from the macroalgae survey in 2012 and 2016, revealed that *S. muticum* is spreading both in terms of areal cover and depth distribution. These results highlight the value of the data obtained from the surveys, not only as input for EIAs but potentially also as the basis for invasive species management.

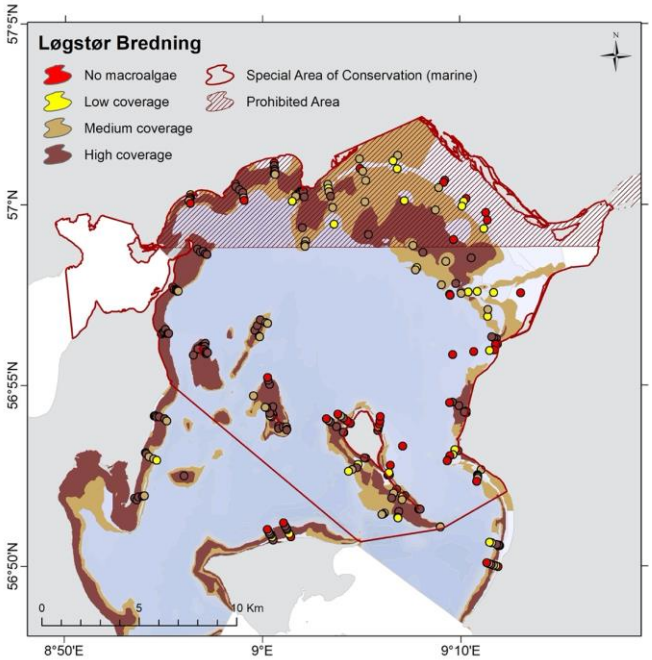


Figure 5. Total macroalgae distribution in Løgstør Bredning in 2016 based on results from the video survey. Circles represent point observations and light and dark brown colours show areas with medium and high coverage of macroalgae obtained by interpolation of point observations.

### 4.1.4. Benthic fauna

Similar to the marcoalgae, benthic macroinvertebrates are a key biological quality element used to classify ecological status. Figure 6 outlines the distribution of benthic communities and seabed sediment types in Løgstør Bredning. The shallow areas in the north of Løgstør Bredning are characterized by community group A that was mainly composed of polychaete species such *Alitta virens*, *Nephtys hombergii*, *Mediomastus sp.*, and *Scoloplos armiger*, the netted dogwhelk *Nassa reticulata*, and the green sea urchin *Psammechinus miliaris*. The majority of sites found in the deeper central parts of Løgstør Bredning were characterised by community group Z, and generally low species diversity (≤2 species per sample). The biomass of group Z was chiefly accounted for by species such as the common starfish, *Asterias rubens* and ragworm *Alitta virens*.

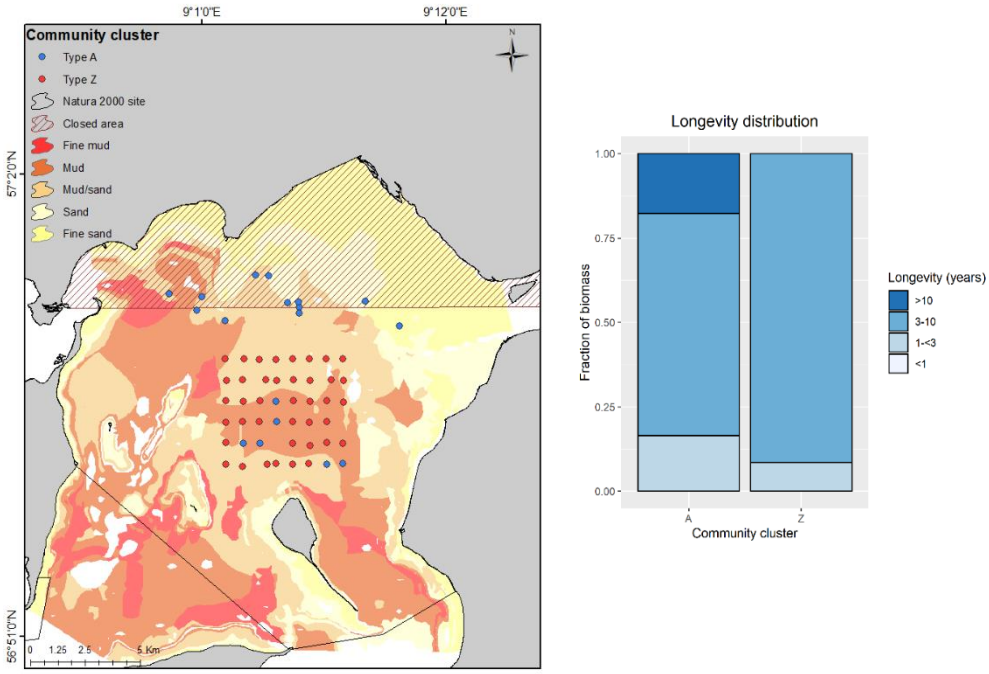


Figure 6. Left: Distribution of the two main benthic community clusters (A and Z) in Løgstør Bredning superimposed on sediment classification. Right: associated longevity distributions for the two benthic community clusters A and Z.

Figure 6 describes the estimated longevity distributions of community groups A and Z. The distributions were largely similar, although roughly 18% of benthic biomass in group A was associated with a relatively long lifespan of >10 years. The regeneration times of the two main groups were estimated to be 3.3 years for group A and 2.2 years for group Z. At the level of the N2000 site, the regeneration time of benthic communities in Løgstør Bredning was estimated to be 2.9 years. To be conservative and easy of management, a regeneration time of 3 years of benthic fauna in Løgstør Bredning was recommended to the authorities. The regeneration time of 3 years was implemented in the EIA for the fishing season 2020/2021 onwards, updating and superseding the previous regeneration time of 4 years (as estimated by expert judgment) used in previous fishing seasons.

*4.2. EIA of bivalve fisheries on ESCs and designated species*

To assess the effects of bivalve fisheries on the mapped ESCs, BB data were used to estimate the impacted area (footprint) of bivalve fisheries for the 2018/2019 fishing season (Figure 7 left) and for four successive fishing seasons from 2015 to 2019 (Figure 7 right).

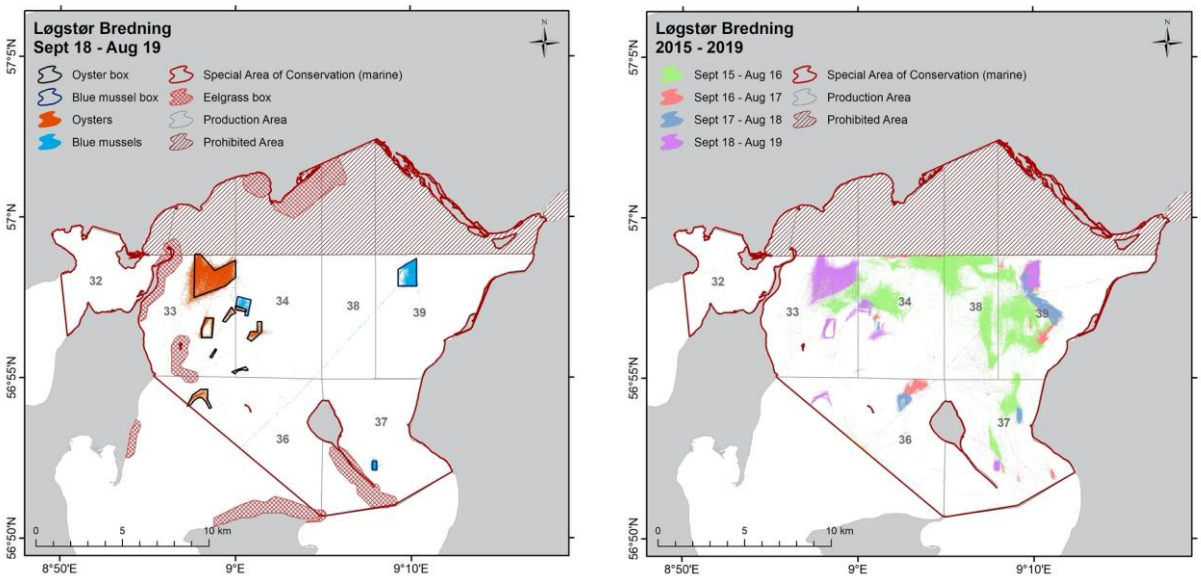


Figure 7. Black box data from Løgstør Bredning, Limfjorden. Left: Area impacted by mussel fishery (blue) and area impacted by flat oyster fishery (orange) in the fishing season 2018/2019, where the fisheries were regulated by fishing boxes. Right: Cumulative area impacted by bivalve fisheries in four successive fishing seasons from 2015 to 2019.

The cumulative area impacted by bivalve fisheries for each ESC is provided in Table 3. The area expected to be impacted by blue mussel fisheries in the season applied for was estimated to be 6.2 km$^2$, or approximately 2% of the marine N2000 area (316 km$^2$) in Løgstør Bredning. This estimate is based on the assumption of a 4,000 t quota, an average density of blue mussels of 1 kg m$^{-2}$ and a dredge efficiency of 65%. The area impacted by flat oyster fisheries was estimated to 21.4 km$^2$ or 6.8% of the site (Table 3), and was based on the assumption of a 400 t quota and a fishery impact of 0.0536 km$^2$ per tons fished (estimated from the BB data from the previous fishing seasons).

Macroalgae has a patchy distribution in Løgstør Bredning (Figure 5) and consequently, the area impacted is reduced with a reduction factor that is estimated to be 0.75, since macroalgae were observed at 75% of all video transects surveyed between 2013 and 2019. In this calculation, all

observations in the macroalgae survey are equally weighted e.g. observation of a few macroalgae is accounting the same as large macroalgae beds. The area impacted by mussel and oyster fisheries is therefore reduced to 1.5% (2% x 0.75) and 5.1% (6.8% x 0.75) for macroalgae, respectively (Table 3). Future changes in the macroalgae distribution will accordingly adjust the reduction factors. The total cumulative area impacted for each of the ESCs are assessed based on associated regeneration times, and therefore the estimated total cumulative area impacted with the given quotas and unrestricted fishery were assessed to exceed the upper limited of 15% for the macroalgae and benthic fauna ESCs (Table 3). In response to this prediction, the fishery implemented spatial restrictions in the form of 'fishing boxes' (Figure 7 left) in order to ensure that the cumulative impacted area would not exceed 15% in the following season. This step also ensured that quotas for both blue mussels (4,000 t) and flat oysters (400 t) were not reduced but maintained and had a total cumulative area impact of 2.6% in the fishing season 2018/2019.

| | Cumulative area impact in previous fishing seasons (%) | Quota of 4,000 t blue mussels (%) | Quota of 400 t flat oysters (%) | Total potential cumulative area impact (%) | Final cumulative area impact after fishing boxes (%) |
|---|---|---|---|---|---|
| **Blue mussel** | 2.2 | 2.0 | 6.8 | 11.0 | 4.8 |
| **Macroalgae** | 10.3 | 1.5 | 5.1 | 19.9 | 12.3 |
| **Benthic Fauna** | 10.3 | 2.0 | 6.8 | 19.1 | 12.9 |
| **Eelgrass** | 0 | 0 | 0 | 0 | 0 |

Table 3. Total cumulative area impacted (%) for each of the four ecosystem components; blue mussel, macroalgae, benthic fauna and eelgrass in the Løgstør Bredning N2000 site. Fishing effort was based on the given quotas of 4,000 t blue mussels and 400 t flat oysters for the season 2018-2019. For each fishing season, the impacted areas is calculated as a percentage of the total N2000 area, and then cumulated according to the regeneration time for each ESC. As a result, the cumulative impacted area for previous fishing seasons varies between the ESCs. The ESC eelgrass is protected by eelgrass boxes.

Table 4 outlines the designated bird and mammal species present in the Løgstør Bredning N2000 site. Of these, only common goldeneye is feeding on mussels and an associated set-aside biomass (2,400 metric tons) of blue mussels is estimated based on the ecological food requirements of the species [35]. In the case where an insufficient biomass of mussels was available for mussel eating species such as the common goldeneye, the fishery quota is adjusted accordingly.

| | Common name | Scientific name |
|---|---|---|
| Birds | **Little tern** | *Sternula albifrons* |
| | **Red-breasted merganser** | *Mergus serrator* |
| | **Common goldeneye** | *Bucephala clangula* |
| Mammals | **European otter** | *Lutra lutra* |
| | **Harbour seal** | *Phoca vitulina* |

Table 4. Designated marine species assessed in the environmental impact assessment of bivalve fishery for the N2000 site, Løgstør Bredning *[14-18]*.

For the fish-eating birds (little tern and red-breasted merganser) and mammal species (harbour seal and European otter), the bivalve fishery is assessed to have no negative impact on the food availability. This is based on a low bycatch of fish in the bivalve fishery and an absence of by-catch of mammals or birds. In addition, the bivalve fishery does not cause significant disturbance to nesting birds, seals or otters. This is mitigated by restriction of fisheries only allowed below 5 m, which minimises disturbance of onshore resting and breeding seals, in addition to a maximum of 15 vessels allowed in each fishing area.

In summary, the EIA for Løgstør Bredning for the 2018/2019 fishing season proposed a sustainable quota of 4,000 t of blue mussels and 400 t of flat oysters. Furthermore, the two fisheries were not considered to potentially compromise populations of designated birds, mammals and fish.

However, the estimation of the cumulative areal impact for the new fishing season was shown to exceed the 15% for the ESCs macroalgae and benthic fauna (Table 3). Accordingly, appointment of specific areas (fishing boxes) were adopted (Figure 7 left), which ensured that the fisheries did not exceed the upper limit of 15% cumulative area impact of the N2000 site for any of the ESCs and that the quotas were maintained.

***5 Adaptive ecosystem-based management in marine protected areas***

By focusing on the implementation of the MOP in Løgstør, this study provides a first demonstration of the use of BB technology to monitor fisheries compliance and to document cumulative areal impacts to key ecosystem components in an MPA. With the implementation of the MOP, a particular focus was placed on the maximal cumulative area impacted by bivalve fisheries within N2000 sites. This approach necessitates science-based knowledge of i) the actual area impacted by bivalve fisheries, ii) the distribution of habitats and ecosystem components at high spatial resolutions, and iii) inventories of the benthic communities to ensure effective ecosystem-based marine management. The MOP initiates a new perspective in the management of bivalve fisheries by shifting the focus from assessments based on target species quotas (in the classical fisheries approach), license regulations, [9], gear regulations [7] and seasonal and temporal restrictions [9], to those guided by ecosystem-based management and international conservation conventions [36-39]. The Danish “regime shift” in management perspective was brought about by EU legislation and is particularly important in MPAs where i) there is a general high level of anthropogenic pressures, and ii) it is difficult to isolate the localised effects of fisheries from basin scale effects e.g. eutrophication.

*5.1. Ownership, responsibility, transparency and security for the bivalve fisheries*

Stakeholder engagement is considered to be the most important factor affecting MPA success [1]. The MOP aims to promote adaptive management, beneficial for both industry and overall nature conservation status where stakeholders take ownership. The Løgstør case study illustrates how fisheries associations worked together with authorities to manage the fisheries. The quotas applied for Løgstør Bredning (2018/2019) were assessed as sustainable for both the mussel and oyster stocks, however the estimated cumulated area impacted by the two fisheries would exceed the maximal upper limit of 15% area impact (Table 3). In response, the fisheries association Foreningen MuslingeErhvervet initiated a survey to identify several fishing boxes in areas of high bivalve biomass, where mussel and oyster fisheries could take place without exceeding the 15% cumulated area impact (Figure 7 right and Table 3) and maximised the sustainable economic benefits from the MPA [1]. BB data were used to control compliance within the fishing boxes and *ad hoc* assessments of the BB data was carried out 2-3 times during the fishing season to evaluate the cumulated impacted areas. During the analysis periods, fisheries were put on hold and reopened if they did not exceed the 15%.

The implementation of the BB system is a key tool in the new management approach as it allows an accurate and transparent mapping of the benthic impact imposed by the fishery. While the BB system initially was perceived as a control measure limiting the fishery, it is now positively recognised by the industry as a useful tool used to maintain quotas in N2000 sites and show transparency. Quotas can be maintained using BB tools by i) implementing fishing boxes and ii) opening of fishing areas previously closed by a general depth limit to protect eelgrass (e.g. areas with no eelgrass or areas not susceptible to eelgrass (re-)establishment). The other important aspect of the data transparency for the industry is to actively respond to accusations of bad

practice by the public. In 2016, the fishers developed the BB system further, by providing access for individual vessels to their own data. The information is not only used actively to keep track of the total area impacted within a fishing season but also by the fishers to optimize their own fishery.

From a management perspective, the BB system has led to transparency and documentation of areas impacted through a strong data-based documentation of area actually affected by bivalve fisheries. Furthermore, the fishery impact on the four ESCs can also be assessed individually, when the ESCs are mapped with sufficient high spatial resolution and regulatory enforcement can be implemented if necessary. A similar electronic monitoring system on-board Scottish scallop vessels has been implemented in 2017, along with changes to the minimum landing size and number of dredges [40]. While these measures are likely to have improved the fishery from a conservation perspective, the monitoring systems were not used to document localized areal impact in MPAs as far as we are aware.

*5.2. Data collection, cost and improvement of documentation via research effort*

BB data provides fisheries managers with a precise data-based documentation of the discrete impacts of bivalve fisheries, as oppose to wider and basin-scale impacts caused by eutrophication and nutrient run-off. Most Danish coastal waters are, according to the WFD, classified as in “bad or poor ecological condition” [41,42] caused by persistent marine eutrophication [43,44]. However, other pressure factors such as bottom trawl fisheries have been identified as a potential risk to obtain “good ecological status” [45], although fishery effects are often comparatively localised to the areas already heavily disturbed by eutrophication [46]. Combining BB data with vessel log-book information of gear type and configuration can provide detailed information of

fishing effort and actual area impacted e.g. using detailed mapped habitats within MPAs. By contrast, such assessments are not possible when using other available remote electronic monitoring fishery data, such as from Vessel Monitoring Systems (VMS) and Automatic Identification Systems (AIS) [39,47].

Another important factor in the management of the bottom contacting fisheries is the need for high resolution mapping of benthic ESCs to assess impacts to the conservation objectives for the MPA, but also to comply with the goals in the WFD. The management of ESCs such as eelgrass has involved model development (see section 3.2), which has both ensured the protection of existing habitats, but also areas which may be suitable for future eelgrass establishment thus complying fully with the WFD. This management approach, however, requires a considerably large monitoring and research effort, and therefore associated costs. Alternatively, without EIAs the fisheries would not be maintained in the N2000 sites. From 2013 to 2019, the money invested by the Danish government and other research funding sources to maintain monitoring and research in the five N2000 sites equated to 13% of the total bivalve landings from the area. The willingness to provide this level of funding has therefore contributed to preservation of coastal fishing communities, provided a variety of jobs, and created income options in rural areas of Denmark.

A further aspect of the MOP has been the acceptance of the data-based management approach by the nature conservation NGOs. This approach has seen the compulsory introduction of BB devices, leading to habitat detailed mapping in each of the N2000 sites, and thus the preservation of designed habitats and species. However, several NGOs are currently supporting a move away from dredge fisheries based on wild beds, to the production of on-bottom and off-bottom cultivations of blue mussels in restricted areas.

## *6 Conclusions*

Overall, this study provides a number of insights on how inclusive and dialog-based governance can help reach stakeholder consensus, and how scientific-based site-specific knowledge is essential in the ecosystem-based management of fisheries in MPAs. Implementation of MPAs can be perceived as obstacles to economic opportunities, rather than a way to improve the environmental and economic sustainability of a given area [1]. Licensed fisheries offer an opportunity to ensure important income for local communities, yet require monitoring and enforcement to ensure the conservation objectives of MPAs. The collection of high-resolution fisheries data via BB, in combination with ecosystem-based management of the bivalve fishery, has enabled the Danish bivalve fishery to continue sustainably in MPAs. The lessons learned from the Danish bivalve fishery therefore may be suitable for other bottom contacting fisheries which occur in MPAs, thereby ensuring sustainability and nature conservation in line with e.g. N2000 regulations. Similarly, bivalve fisheries which occur outside MPAs may potentially benefit from implementation of the BB system to comply with general nature conservation objectives. These may include objectives under the EU WFD and MSFD, improvement of Marine Stewardship Council (MSC) certification, or in order to secure access to areas which contain potentially vulnerable seabed habitats. Furthermore, in relation to the WFD, implementation of compulsory BB on fishing vessels would also document if fishing activities would prevent an area obtaining “good ecological status” or potentially improve the detection of fishery effects in areas where ecological status is impacted by basin-scale pressure factors, such as eutrophication.

This study also highlights the need for high resolution habitat mapping to allow for proper assessments of the extent and scale of areas impacted by the fishery. In our experience, the scale of mapping requires significant research effort and resources to ensure a fully adaptive

ecosystem-based management approach. Such approaches may be necessary to reconcile future national and international fisheries management obligations and/or nature conservation implementations, but also to forecast ecosystem changes caused by e.g. climate change, invasive species, and other anthropogenic pressures.

***References***

[1] J. Humphreys, R.J.H. Herbert, Marine protected areas: Science, policy & management, Estuar Coast Shelf S. 215 (2018) 215–218. doi:10.1016/j.ecss.2018.10.014.

[2] M. Dureuil, K. Boerder, K.A. Burnett, R. Froese, B. Worm, Elevated trawling inside protected areas undermines conservation outcomes in a global fishing hot spot, Science. 362 (2018) 1403–1407. doi:10.1126/science.aau0561.

[3] S. Giakoumi, J. McGowan, M. Mills, M. Beger, R.H. Bustamante, A. Charles, et al., Revisiting "Success" and 'Failure' of Marine Protected Areas: A Conservation Scientist Perspective, Front. Mar. Sci. 5 (2018) 226. doi:10.3389/fmars.2018.00223.

[4] R.R. Stewart, H.P. Possingham, Efficiency, costs and trade-offs in marine reserve system design, Environ Model Assess. 10 (2005) 203–213. doi:10.1007/s10666-005-9001-y.

[5] T. Gray, C. Haggett, D. Bell, Offshore wind farms and commercial fisheries in the UK: A study in Stakeholder Consultation, Ethics Place and Environment. 8 (2010) 127–140. doi:10.1080/13668790500237013.

[6] J. Capelle, Production efficiency of mussel bottom culture, PhD Thesis, Wagening University dissertation no. 6592, 2017.

[7] S.E. Birchenough, R.W.E. Clark, S. Pengelly, J. Humphreys, Managing a dredge fishery within a marine protected area: Resolving environmental and socio-economic objectives, in: J. Humphreys, R. Clark (Eds.), Marine Protected Areas, Elsevier, 2020: pp. 459–473. doi:10.1016/B978-0-08-102698-4.00023-X.

[8] Anonymous, The Inshore Fishing (Prohibition of Fishing and Fishing Methods) (Outer Hebrides) Order 2017, 2017.

[9] O. Tully, S. Clarke, The status and management of oyster (*Ostrea edulis)* in Ireland, Irish Fisheries Investigations No 24. The Marine Institute, Fisheries Ecosystems Advisory Services, Rinville, Oranmore, Co. Galway, 2012.

[10] E. Hoffmann, A marine ecosystem and an economic and ethnological analysis of consequences of utilizing its biological resources, ICES CM. T:36 (1994).

[11] G. Dinesen, K. Timmermann, E. Roth, S. Markager, L. Ravn-Jonsen, M. Hjorth, et al., Mussel production and water framework directive targets in the Limfjord, Denmark: an

integrated assessment for use in system-based management, Ecol Soc. 16 (2011) 26. doi:10.2307/26268973.

[12] European Commission, Letter of formal notice issued by the Commission regarding Infringement case 2010/4157 concerning mussel-dredging in Natura 2000 sites in Denmark. 29 November (2010).

[13] European Commission, Closure of the Infringement case 2010/4157 concerning mussel-dredging in Natura 2000 sites in Denmark. 28 January (2014).

[14] Miljø-og Fødevareministeriet, Natura 2000-plan 2015-2021 Horsens Fjord, havet øst for og Endelave. Natura 2000-område nr. 56. Habitatområde H52 Fuglebeskyttelsesområde F36, 2016.

[15] Miljø-og Fødevareministeriet, Natura 2000-plan 2016-2021 Agger Tange, Nissum Bredning, Skibsted Fjord og Agerø. Natura 2000-område nr. 28, Habitatområde nr. 28, Fuglebeskyttelsesområde nr. 23, 27, 28 og 39, 2016.

[16] Miljø-og Fødevareministeriet, Natura 2000-plan 2016-2021 Lillebælt Natura 2000-område nr. 112 Habitatområde nr. 96 Fuglebeskyttelsesområde nr. 47, 2016.

[17] Miljø-og Fødevareministeriet, Natura 2000-plan 2016-2021 Løgstør Bredning, Vejlerne og Bulbjerg Natura 2000-område nr. 16. Habitatområde H16. Fuglebeskyttelsesområde F8, F12, F13, F19 og F20, 2016.

[18] Miljø-og Fødevareministeriet, Natura 2000-plan 2016-2021 Lovns Bredning, Hjarbæk Fjord og Skals, Simested og Nørre Ådale samt Skravad Bæk Natura 2000-område nr. 30 Habitatområde H30 Fuglebeskyttelsesområde F14 og F24, 2016.

[19] Udenrigsministeriet, Målsætninger og forvaltningsprincipper for muslinge- og østersskrab og øvrig muslinge- og østers produktion i og udenfor Natura 2000 områder, 2019.

[20] J. Carstensen, D. Conley, J. Andersen, G. Ærtebjerg, Coastal eutrophication and trend reversal: A Danish case study, Limnol Oceanogr. 51 (2006) 398–408.

[21] B. Riemann, J. Carstensen, K. Dahl, H. Fossing, J.W. Hansen, H.H. Jakobsen, et al., Recovery of Danish Coastal Ecosystems After Reductions in Nutrient Loading: A Holistic Ecosystem Approach, Estuar Coast. (2015) 1–16. doi:10.1007/s12237-015-9980-0.

[22] R.P. Frandsen, O. Eigaard, L.K. Poulsen, D. Tørring, B. Stage, D. Lisbjerg, et al., Reducing the impact of blue mussel (*Mytilus edulis*) dredging on the ecosystem in shallow water soft bottom areas, Aquatic Conserv: Mar Freshw Ecosyst. (2014). doi:10.1002/aqc.2455.

[23] P. Nielsen, J. Petersen, Flat oyster fishery management during a time with fluctuating population size, Aquat Living Resour. 32 (2019).

[24] P. Dolmer, P. Kristensen, E. Hoffmann, Dredging of blue mussels (*Mytilus edulis* L.) in a Danish sound: stock sizes and fishery-effects on mussel population dynamic, Fish Res. 40 (1999) 73–80.

[25] J. Aitchison, On the Distribution of a Positive Random Variable Having a Discrete Probability Mass at the Origin, Journal of the American Statistical Association. 50 (1955) 901–908.

[26] P. Canal-Verges, J.K. Petersen, E.K. Rasmussen, A. Erichsen, M.R. Flindt, Validating GIS tool to assess eelgrass potential recovery in the Limfjorden (Denmark), Ecol Model. 338 (2016) 135–148. doi:10.1016/j.ecolmodel.2016.04.023.

[27] M.R. Flindt, E.K. Rasmussen, T. Valdemarsen, A. Erichsen, H. Kaas, P. Canal-Verges, Using a GIS-tool to evaluate potential eelgrass reestablishment in estuaries, Ecol Model. 338 (2016) 122–134. doi:10.1016/j.ecolmodel.2016.07.005.

[28] P. Canal-Verges, M. Potthoff, F.T. Hansen, N. Holmboe, E.K. Rasmussen, M.R. Flindt, Eelgrass re-establishment in shallow estuaries is affected by drifting macroalgae - Evaluated by agent-based modeling, Ecol Model. 272 (2014) 116–128. doi:10.1016/j.ecolmodel.2013.09.008.

[29] C. McLaverty, O.R. Eigaard, G. Dinesen, H. Gislason, A. Kokkalis, A.C. Erichsen, et al., Using high-resolution fisheries data to assess the effects of bivalve dredging on benthic communities in stressed coastal systems, Mar Ecol Prog Ser. 642 (2020) 21–38. doi:10.3354/meps13330.

[30] K.R. Clarke, R. Warwick, Change in Marine Communities. An Approach to Statistical Analysis and Interpretation, 2nd ed., Plymouth, 2001.

[31] S.G. Bolam, C. Garcia, J. Eggleton, A.J. Kenny, L. Buhl-Mortensen, G. Gonzalez-Mirelis, et al., Differences in biological traits composition of benthic assemblages between

unimpacted habitats, Mar Environ Res. 126 (2017) 1–13. doi:10.1016/j.marenvres.2017.01.004.

[32] J.G. Hiddink, S. Jennings, M. Sciberras, S.G. Bolam, G. Cambie, R.A. McConnaughey, et al., Assessing bottom trawling impacts based on the longevity of benthic invertebrates, J Appl Ecol. 56 (2019) 1075–1084. doi:10.1111/1365-2664.13278.

[33] E. Gosling, Bivalve molluscs: biology, ecology and culture, 2nd edition. Wiley Blackwell Science, Oxford. (2015)

[34] P. Henriksen, A. Josefson, J. Hansen, D. Krause-Jensen, K. Dahl, K. Dromph, Danish contribution to the EU Water Framework Directive intercalibration phase 2, Aarhus University, DCE – Danish Centre for Environment and Energy, 2014.

[35] P. Dolmer, P. Kristensen, E. Hoffmann, K. Geitner, R. Borgstrøm, A. Espersen, et al., Udvikling af kulturbanker til produktion af blåmuslinger i Limfjorden, DTU Aqua Report. 212 (2009).

[36] M.A. Zacharias, J.C. Roff, A Hierarchical Ecological Approach to Conserving Marine Biodiversity, Conservation Biology. 14 (2000) 1327–1334. doi:10.1046/j.1523-1739.2000.99191.x.

[37] C.M. Roberts, J.P. Hawkins, F.R. Gell, The role of marine reserves in achieving sustainable fisheries, Phil. Trans. R. Soc. B. 360 (2005) 123–132. doi:10.1098/rstb.2004.1578.

[38] S.E. Apitz, M. Elliott, M. Fountain, T.S. Galloway, European environmental management: Moving to an ecosystem approach, Integrated Environmental Assessment and Management. 2 (2006) 80–85. doi:10.1002/ieam.5630020114.

[39] S.A. Pedersen, H.O. Fock, A.F. Sell, Mapping fisheries in the German exclusive economic zone with special reference to offshore Natura 2000 sites, Mar Policy. 33 (2009) 571–590. doi:10.1016/j.marpol.2008.12.007.

[40] Anonymous, Regulation of Scallop Fishing (Scotland) Order 2017, 2017.

[41] Miljø-og Fødevareministeriet, Vandområdeplan 2015-2021 for Vandområdedistrikt Jylland og Fyn, 2016.

[42] Miljø-og Fødevareministeriet, Vandområdeplan 2015-2021 for Vandområdedistrikt Sjælland, 2016.

[43] D. Conley, J. Carstensen, G. Ærtebjerg, P. Christensen, T. Dalsgaard, J.L.S. Hansen, et al., Long-term changes and impacts of hypoxia in Danish coastal waters, Ecol Appl. 17 (2007) S165–S184.

[44] J.H. Andersen, J. Carstensen, D.J. Conley, K. Dromph, V. Fleming-Lehtinen, B.G. Gustafsson, et al., Long-term temporal and spatial trends in eutrophication status of the Baltic Sea, Biological Reviews. 92 (2017) 135–149. doi:10.1111/brv.12221.

[45] J.K. Petersen, ed., Menneskeskabte påvirkninger af havet – Andre presfaktorer end næringsstoffer og klimaforandringer, DTU Aqua Report. 336 (2018).

[46] J.K. Petersen, ed., Andre presfaktorer end næringsstoffer og klimaforandringer – effekter af fiskeri på de marine kvalitetselementer bundfauna og fytoplankton, DTU Aqua Report. 361 (2020).

[47] G. Rowlands, J. Brown, B. Soule, P.T. Boluda, A.D. Rogers, Satellite surveillance of fishing vessel activity in the Ascension Island Exclusive Economic Zone and Marine Protected Area, Mar Policy. 101 (2019) 39–50. doi:10.1016/j.marpol.2018.11.006.